Initial orientation effect and selecting desired events in 520AMeV/u U-U collisions

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How to select out those collisions with the desired geometry such as tip-tip and/or body-body in experiment is one key point for performing high energy UU collisions. With a relativistic transport model, we performed a simulation for deformed UU collision with vast different orientations at CSR energy area corresponding to the high net-baryon density region in QCD phase diagram. By investigating the centrality and initial collision orientation dependence of the center baryon density, we found that the tip-tip like UU collisions with extended high density phase, which is very important for studying the nuclear EoS of high baryon density matter and the possible end-point of the phase boundary, are those events with small initial orientations ($\leq 20^0$) for bath projectile and target in reaction plane and small impact parameter ($\leq 2.6 fm$). We pointed out quantificationally two observations – multiplicity of forward neutron and nuclear stopping power that both allows us to select out those most interesting events (i.e. tip-tip like), which will be very helpful for the future experiments at performing UU collisions.

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I. INTRODUCTION

A major goal of current and future high energy heavy-ion collisions experiments is to probe and study the state of new matter under extreme conditions. Lattice QCD calculation predicts that a phase transition from the hadronic state to the quark-gluon-plasma (QGP) will occur under high temperature or density.

In recent years, the focus on searching for QGP is performed at SPS/CERN and RHIC/BNL with ultra-relativistic heavy ion collision correspond to high temperature and low baryon density region in nuclear matter phase diagram [1, 2]. Several experimental observables like the Number-of-Constituent-Quark (NCQ) Scaling of elliptic flow, jet-quenching, etc. can be explained commendably with the appearance of partonic degree of freedom in the collisions at RHIC energy regions [3]. However, due to the complex nature of the relativistic nucleus-nucleus reactions, the QGP, if it has been created, escape direct detection. The fact we have not observed any observation undergoing dramatic change reminds us to perform an energy scan from high energy to lower energy to search for the phase boundary and the possible end-point of the phase boundary [4]. On the other hand, in last two decades the heavy ion collisions performed at the BEVALAC/LBNL and SIS/GSI [5, 6] were used to produce hot and compressed nuclear matter for studying more about the nuclear equation of state (EoS) [7, 8] at high baryon density and low temperature region of the phase diagram. We have made great efforts in studying the nuclear EoS, both theoretically and experimentally, but a solid conclusion can hardly be made. From this two points for more understanding of the nuclear matter phase diagram and EoS at high net-baryon density region, it is expected that the Heavy Ion Research Facility in Lanzhou china (HIRFL)— Cooler Storage Ring (CSR) with a maximal beam kinetic energy of 520 MeV/nucleon for heavy nuclei [9], which focuses at the high baryon density region, can make significant contribution to those important search.

The uranium-on-uranium (UU) collision is most suitable for this study. Uranium is the most deformed stable nucleus. Representing U as a homogeneous ellipsoid with one long (R_l) and two short (R_s) semi-axis, one can related their ratio to deformation parameter used in nuclear physics

$$\frac{R_l}{R_s} = \left(\frac{1 + 4\delta/3}{1 - 2\delta/3}\right)^{1/2} \qquad (1)$$

For $\delta_U \approx 0.27$, the ratio of the long-axis over short-axis is as large as 1.29. For A=238, we will use $R_l = 8.4$, $R_s = 6.5$ and $R = (R_s^2 R_l)^{1/3} = 7.0 fm$ [10].

Due to larger A and deformation, the gain in energy density for UU over AuAu can reach the factor 1.8 in RHIC/BNL [11]. Because of the deformation, UU collisions at the same beam energy and impact parameter but different orientations are expected to form dense matter with different compressions and lifetimes.

We consider two extreme collisions: the head on collisions with long-axis on long-axis and short-axis on short-axis as tip-tip and body-body collisions, respectively [12]. Random collision geometries, which are illustrated in Fig.1, lie between them. It is expected that the tip-tip collisions can form a higher densities of nuclear matter with longer duration than in body-body or the spherical nuclei collisions and easy to reach thermal equilibrium at the same energy and impact parameter. This is a powerful tool for studying the physics of large compression, high-baryon density and possible phase transition from nuclear matter to a new form of matter with partonic degree of freedom.
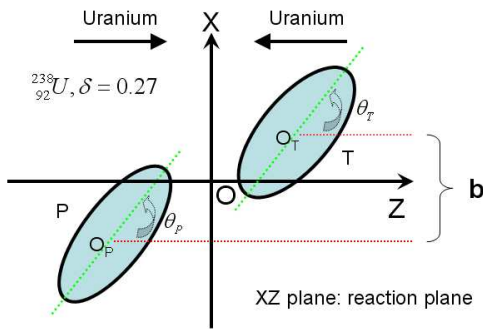
FIG. 1: The initial collision geometries of the reaction plane in U+U collisions: Z-direction is defined as the beam direction. The impact parameter b is along X axis. X-Z plane represents the reaction plane. θ_P and θ_T are the orientation of reaction plane for projectile and target, respectively. Thus, $\theta_P = \theta_T = 0^0 / \pm 90^0$ corresponded to tip-tip/body-body collisions respectively.

For the non-polarized UU collision, target and projectile have random orientation at the initial coordinate space. Several ideas have been developed during the past few years to take advantage of the UU collisions [13, 14, 15], but no experimental implementation has been made. One of the uncertainties is how to select collision with the desired geometry such as tip-tip and/or body-body.

In previous Ref [12, 16], we have studied systemically the stopping power and anisotropy flow in tip-tip and body-body UU collisions. In this paper, we apply a relativistic transport models, ART [19], to study the effect of different colliding orientations and only focus on the central baryon density in order to confirm quantificationally that what initial geometries are the interesting events with longtime and high density. This will provide a useful help for quantitative analysis in experiment.

The outline of this paper is as follows. Section II is devoted to the centrality dependence of central baryon density. In section III, we will discuss the effect with different inial collision orientations. In section IV, two measurable ways to select out the tip-tip like events will been discussed. Finally, a short summary will be given in section V.

II. THE CENTRALITY DEPENDENCE OF CENTRAL BARYON DENSITY

To form a quark-gluon plasma, it is necessary to achieve a high local energy or baryon densities in a sufficiently large volume and for a sufficiently long time so that the initial plasma droplets can grow up. The current estimate for the critical baryon and energy densities at which the QGP may form are about 5 ρ_0 and 2.5 GeV/fm^3, respectively [20]. Under the assumption of full nuclear stopping, which is a good approximation for heavy nuclei at CSR energy region, as the results of energy and baryon number conservation, the maximum energy density and maximum baryon density for heavy nuclear collisions are

$$\frac{\epsilon_{max}}{\epsilon_0} = 2.5; \frac{\rho_{max}}{\rho_0} = 2.5, \qquad (2)$$

respectively [21].

The full nuclear stopping is reached most possibly in central collision. We use the effective centrality which is defined with $\tilde{b} = b/b_{max}$ to replace the impact parameter b. Here b_{max} is the maximum for minimum bias events, corresponding to the tip-tip and body-body UU collisions are about 13 fm and 17 fm, respectively.
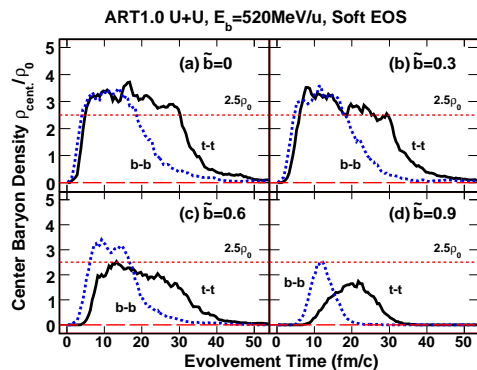

FIG. 2: Time evolution of central local baryon density in UU tip-tip (solid line) and body-body (dashed line) collisions with a beam kinetic energy of 0.52 GeV/u in four different centralities.

Fig.2 shows the evolution of central baryon density in UU tip-tip and body-body collisions at $E_{\rm beam} = 0.52 GeV/u$ at different centralities $\tilde{b}$ using the soft nuclear equation of state with $K = 200$ MeV. Here, the central region is a cube with $1 fm^3$ and the lattice estimate is done for central density [19].

As expected, the maximum baryon density decreases evidently from central to peripheral UU collisions for both tip-tip and body-body. It is remarkable that the decline is faster and more obvious in tip-tip than in body-body. The orientation of UU collision almost has no effect during the early stage of the central collision corresponding to $\tilde{b} \leq 0.3$ when the kinetic energy is much higher than the potential energy. A maximum baryon density of about 3.2 ρ_0 are reached at about 7 fm/c in both tip-tip and body-body collisions at $\tilde{b} = 0$. The matter in the high density region (i.e., with $\rho/\rho_0 \geq 2.5$ that may occur the full nuclear stopping) lasts for about 13 fm/c and 25 fm/c at body-body and tip-tip collisions, respectively. This means that the high density phase in the tip-tip collisions lasts about two times longer than that in the body-body collisions. But this discrepancy of high density phase lifetime fades away rapidly from $\tilde{b} = 0$ to $\tilde{b} = 0.3$, even the high density phase vanishes for tip-tip

collisions at about $\tilde{b} = 0.6$. The higher compression and longer passage time render the central tip-tip UU collisions as the most probable candidates to form the QGP and to study nuclear EoS in high density condition.

One should take note of that the tip-tip and body-body UU collisions can reached a near maximum baryon density but exits a different lifetime of high density matter for central events (See Fig2(a)). In order to confirm what events are the interesting events with extended lifetime, this discrepancy of tip-tip and body-body must be displayed quantificationally. We define a new variable — the baryon aggradation strength as followed:

$$S = \int_{t'}^{t''} \rho dt, \qquad (3)$$

Here, t' and t'' are the threshold and end time of the central high density matter. The centrality dependence of baryon aggradation strength is showed in Fig.3. One can see clearly that the strength of tip-tip is higher than body-body at $\tilde{b} \leq 0.4$. The curve for tip-tip is flat from $\tilde{b} = 0$ to $\tilde{b} = 0.2$ but has a sharp drop at $\tilde{b} = 0.2$. Otherwise, the high density matter vanishes for tip-tip but still exist for body-body at $\tilde{b} \geq 0.7$. Therefore, as a conservative estimate, the tip-tip events with $\tilde{b} \leq 0.2$, corresponding to $b \leq 2.6 fm$ and the value of $S \geq 70$, are the interesting events with extended high density lifetime.

In Fig.3, we also indicate the result of using the forward (i.e. $\theta < 15^0$) neutron multiplicity N_n to replace the normalized impact parameter $\tilde{b}$ because the multiplicity of forward neutron which can been measured easily in experiment at CSR and have a linear relation with the impact parameter [12]. One can see clearly that the multiplicity of forward neutron in tip-tip is smaller than in body-body at $\tilde{b} \leq 0.2$. Hence, we can separate easily the tip-tip and body-body events only by the cut of $N_n \leq 30$ when most tip-tip central events will survive.
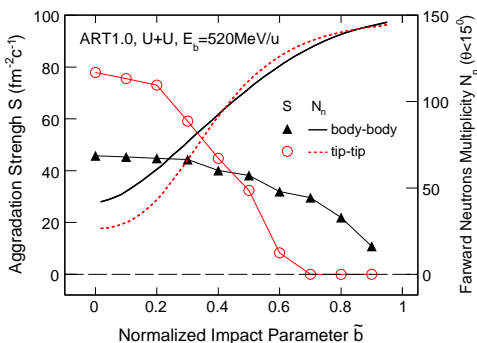

FIG. 3: Left: Baryon aggradation strength versus normalized impact parameter for UU tip-tip (circular hollow dot) and body-body (triangular solid dot) collisions. Right: The forward neutron multiplicity versus normalized impact parameter for UU tip-tip (dashed line) and body-body (real line)collisions at a beam kinetic energy of $0.52 GeV/u$.

III. THE ORIENTATION DEPENDENCE OF CENTRAL BARYON DENSITY

From Fig.1., one can see clearly that it depends strongly on five parameters to confirm the initial geometries of UU collision. They are the impact parameter b, the initial orientation of projectile and target in reaction plane θ_P and θ_T, the inial orientation of projectile and target in transverse plane ϕ_P and ϕ_T, respectively.

In section II, we gained a simple estimate that the interesting events with extended high density lifetime relate to $b \leq 2.6 fm$. Based on this point, we will discuss the orientation dependence of central baryon density under $b \leq 2.6 fm$ in this section.

Fig.4 (a) and (b) are the orientation of initial transverse plane dependence on baryon aggradation strength at $b = 0$ fm and $b = 2.6$ fm, respectively. Here, we only need to take into account the relative orientation in initial transverse plane because of the symmetry of initial overlap region (interaction region) in shape.
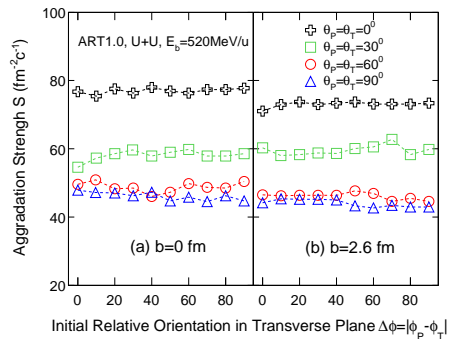

FIG. 4: The relative orientation of projectile and target in the initial transverse plane dependence on baryon aggradation strength at $b = 0$ fm (a)and $b = 2.6$ fm (b), respectively.

From Fig.4, we can see that the baryon aggradation strength is nearly invariable when the orientations of projectile and target (θ_P, θ_T) in the reaction plane are fixed but the orientations of projectile and target in the transverse plane (ϕ_P, ϕ_T) are changed from 0^0 to 90^0 at both $b = 0$ and $b = 2.6 fm$. Here, we only consider the extreme condition that the orientations of projectile and target are equal, i.e. $\theta_P = \theta_T$. There is an express drop is showed from 0^0 to 30^0 for θ_P or θ_T when the relative orientation in transverse plane $\Delta\phi$ is fixed. This phenomenon illuminates both θ_P and θ_T should are less than 30^0 for the tip-tip like event.

Due to inessential ϕ_P and ϕ_T, fig.5(a) are the initial orientation dependence on baryon aggradation strength at $b = 0$ fm with $\phi_P = \phi_T = 0^0$. Hence, we only need to consider two extreme geometries for full overlap in transverse plane. Others are between them. The curve indicates the discrepancy is tiny for $\theta_P = \pm\theta_T$ at $b = 0 fm$. It is remarkable that a sharp drop at $\theta_P = |\theta_T| = 20^0$ is seen. If one requires $S \geq 70$, the orientations in the

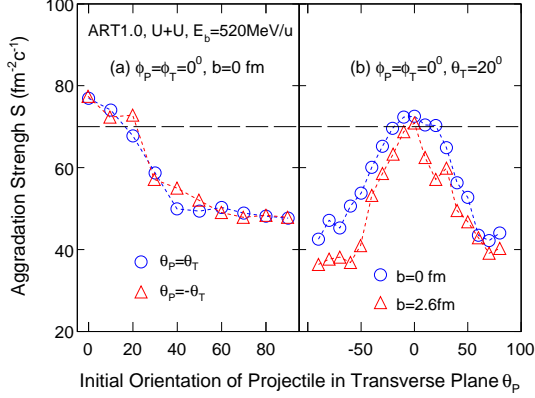those events with biggish impact parameter b.

FIG. 5: The initial orientation of projectile and target in reaction plane dependence on baryon aggradation strength in UU collisions at $E_b = 0.52 GeV/u$. Left window (a) with same initial orientation $\theta_P = |\theta_T|$ at $b = 0 fm$. Right window (b) with fixed $\theta_T = 20^0$ at b=0 and $b = 2.6 fm$.
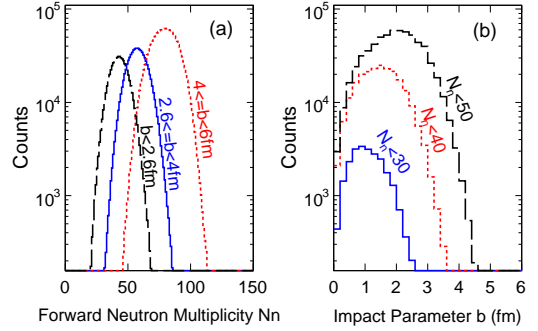

FIG. 6: Left window (a) is the forward neutron multiplicity N_n distribution with different selective impact parameters b. Right window (b) is the impact parameter b distribution with different selective forward neutron multiplicity in random UU collisions at $E_b = 0.52 GeV/u$.

initial transverse plane should be less than 20^0 for both projectile and target. Fig.5 (b) shows θ_P dependence on baryon aggradation strength with fixed $\theta_T = 20^0$ at both $b = 0 fm$ and $b = 2.6 fm$. It emphasizes again that θ_P is less than 20^0 if $S \geq 70$.

In a short word, those events with extended high density phase in UU collisions are the tip-tip like events which are with the initial orientations $\theta_P \leq 20^0$ and $\theta_T \leq 20^0$ in the transverse plane and $b \leq 2.6 fm$.

IV. TWO MEASURES FOR SELECTING OUT THE TIP-TIP LIKE EVENTS IN EXPERIMENT

Due to the effect of initial orientation of projectile and target for deformed nucleus, one key point to program UU collisions in experiment is how to select out those collisions with the desired geometry such as tip-tip like events.

In view of the discrepancy of forward neutron multiplicity N_n dependence on impact parameter b between tip-tip and body-body UU collision showed in fig.3, a available try is associated spontaneously. Fig.6(a) shows the forward neutron multiplicity N_n distribution with different selective impact parameters b in random UU collisions. Here, About 6.8 millions events with $b \leq 6 fm$ are created for our simulation. Obviously, it can effectively reject those events with $b > 4 fm$ by selecting $N_n < 50$. Fig.6(b) shows impact parameter b distribution with different selective forward neutron multiplicity. If one selects the cut with $N_n < 40$, the percentage of those events with $b \leq 2.6 fm$ will been enhanced. It is worth to mention that the percentage can been farther enhanced with the cut $N_n < 30$, but large numbers of tip-tip like events with $b \leq 2.6 fm$ also will been rejected. Thereby, N_n is a good measure in experiment as a trigger for fast rejecting

As a incidental available result, fig.7 shows the initial orientation (θ_P and θ_T) distribution of projectile and target in reaction plane with the cut $N_n < 40$ and $N_n < 30$ for random UU collisions. One can see the most events is tip-tip like events with both $\theta_P \leq 20^0$ and $\theta_T \leq 20^0$. It is satisfying by the reducing N_n to gather more pure tip-tip like events.
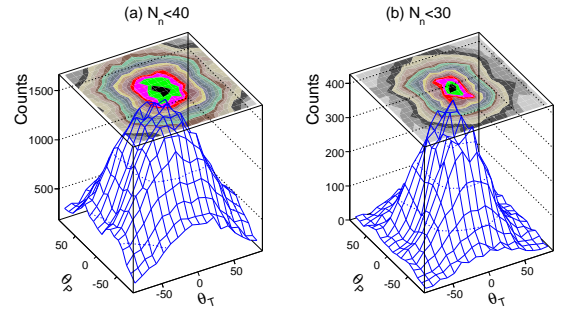

FIG. 7: The initial orientation (θ_P and θ_T) of projectile and target in reaction plane when cut $N_n < 40$ (a) and $N_n < 30$ (b) in random UU collisions at $E_b = 0.52 GeV/u$.

In addition, it is well-know that an obvious long duration will load possible thermal equilibrium of high density matter which has been obtained in tip-tip central collisions. The degree of thermalization can be measured by the ratio R of transverse to longitudinal momenta in low and intermediate energies heavy ion collisions [17]. Its expression is

$$R = \frac{2 \sum_i |p_{it}|}{\pi \sum_i |p_{iz}|}, \qquad (4)$$

Here, i is the serial number of particles, the sum involves all particles, $|p_{it}|$ and $|p_{iz}|$ are the total absolute value

of nucleon transverse and longitudinal momentum in the c.m.s, respectively. It's a multi-particle observable on an event-by-event basis, which for an isotropic distribution is unity. Then $R = 1$ is a necessary, although not is a sufficient, condition for thermal equilibrium. It is also a measure of the stopping power [18].
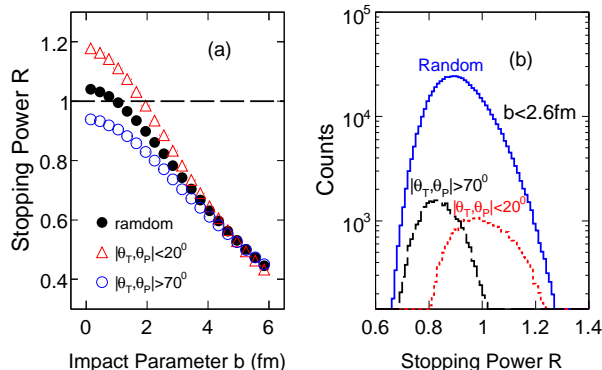

FIG. 8: Left: the nuclear stopping power R as a function of the impact parameter b in different orientation UU collisions at $E_b = 0.52 GeV/u$. Right: the nuclear stopping power R distribution with $b < 2.6 fm$ in different orientation UU collisions at $E_b = 0.52 GeV/u$.

Fig.8(a) shows that the impact parameter b dependence on nuclear stopping power R in different orientation UU collisions. Here, Only charge particles are considered. For three samples with different orientation collisions, a nice linear relation can been seen clearly between stopping power R and impact parameter b. For the most central events, tip-tip like collisions ($\theta_{P,T} < 20$) have a maximal value for R among three samples, i.e. maximal most strong stopping power. When b increase, R decrease. Otherwise, that stopping power R in tip-tip like collisions is large than in body-body like events (($\theta_{P,T} > 70$) at $b < 4fm$. Even, R reaches to ~ 1.2 in tip-tip like events but only ~ 0.92 in body-body like events and ~ 1.02 in random collisions at $b = 0fm$. Thus, we can gather the center events by selecting R, for instance the cut with $R > 1$ corresponding to $b \simeq 1fm$ for random and $b \simeq 2fm$ for tip-tip like UU collisions can get rid of body-body like events.

This remarkable discrepancy prompts us that the central tip-tip like events maybe have a distinct distribution of stopping power R. Fig.8(b) shows stopping power R distribution with $b < 2.6fm$ for three samples with different orientation UU collisions. It can be see clearly that the body-body like events can been rejected commendably from random events at $b < 2.6fm$ by selecting $R > 1$. If one expects higher percentage of tip-tip like events in the sub-sample, $R > 1.1$ can been selected, but at the same time vast tip-tip like events also will been thrown away.

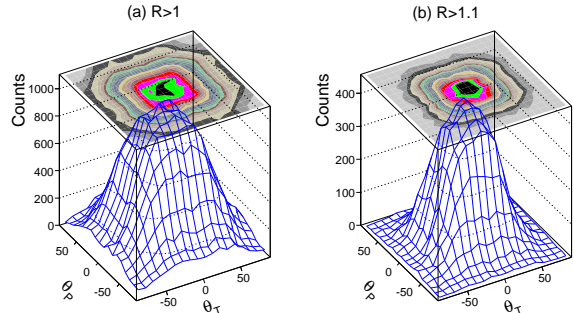Fig.9 shows the initial orientation (θ_P and θ_T) distri-

FIG. 9: The initial orientation (θ_P and θ_T) of projectile and target in reaction plane when cut $R > 1$ (a) and $R > 1.1$ (b) in random UU collisions at $E_b = 0.52 GeV/u$.

bution of projectile and target in reaction plane when cut $R > 1$ (a) and $R > 1.1$ (b) in random UU collisions. It can been seen very clearly that most events have a small orientation, which events are closer to tip-tip like events, by selecting the nuclear stopping power $R > 1$ and $R > 1.1$. When $R > 1.1$, the events with larger orientation are rejected ulteriorly. In other words, it can enhance the purity of tip-tip like events and minify the background when R increases. Therefore, with the nuclear stopping power R, it is possible to select out the tip-tip like collisions in experiment. This will allow us to study the nuclear collisions at higher density with a considerable long duration.

V. SUMMARY

Performing UU collisions are a good tool to search for QGP, the phase boundary and the possible end-point of the phase boundary. Those most interesting events (i.e. tip-tip like) is with small initial orientations ($\leq 20^0$) in reaction plane and small impact parameter ($\leq 2.6fm$). For the non-polarized UU collisions, we have developed two measures allow us to select out those tip-tip like events in experiment. The forward neutron multiplicity as a trigger and nuclear stopping power is suited for fast on-line and off-line physical analysis, respectively.

ACKNOWLEDGMENTS

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